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Experimental verification of higher-order mode suppression in a bent large-mode-area multi-cladding fiber

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Abstract: A novel technique to suppress the higher-order mode in a bent large-mode-area triple-cladding fiber is experimentally presented. 3-dB suppression of LP_{02} mode is observed on a fabricated triple-cladding fiber with 130-mm diameter bend.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2400) Fiber properties.

1. Introduction

High-power fiber lasers have recently had remarkable progress [1]. A large mode area (LMA) fiber is an important component to increase output power of a fiber laser. There is a trade off relationship among an enlargement of mode area, single-mode transmission and adequate bending loss property for actual use. Some solutions have been presented to break the tradeoff relationship. For example, leakage channel fibers (LCFs) [2], characterized by a cladding formed by a single air-hole ring, are ones of the approaches for realizing effectively single-mode LMA fibers. However, it is difficult to realize low transmission loss and low bending loss LCF simultaneously because of the inherent lossy nature of the LCFs. Another proposal for LMA fibers is employing resonant structures, such as ring-assisted fibers [3] and chirally-coupled-core fibers [4]. The complicated index profile of the resonant structured fiber requires a precise profile control and results in high fabrication cost. A simple technique for suppressing a higher-order mode in LMA fiber with triple cladding has recently proposed by simulation [5]. A bent triple-layer cladding fiber enables the higher-order mode suppression of the core modes thanks to modes coupling between high-order modes and cladding modes.

In this paper, we experimentally demonstrate a higher-order mode suppression of a bent LMA multi-cladding fiber. Mode coupling from LP_{02} mode of the core to cladding mode is demonstrated with an existence of loss peak in a bent fiber. The proportional relationship between a coupling wavelength and a bending diameter is experimentally presented.

2. Triple-Cladding Fiber Design and Fabrication

Figure 1 shows a refractive index profile of a proposed LMA triple-cladding fiber (TCF) [5]. The TCF involves three glass layers: a center core, first cladding and second cladding. The second cladding is covered with a third cladding of polymer layer which refractive index is lower than silica glass. The TCF has some merit to a double-cladding fiber, which is a popular structure in a fiber for a laser application. One merit of the TCF is improvement of pump light efficiency. A large-diameter second cladding enables to enlarge pump power. The high pump power in the second cladding concentrates on the first cladding thanks to Δ_{clad}.

Another advantage of the TCF is a bending loss reduction under a restriction of single-mode transmission. If the refractive index difference between the core and the first cladding, $\Delta_{TCF} - \Delta_{clad}$, is low enough, the TCF is single-mode fiber at 1064 nm. However, the bending loss of the fundamental mode is very high for a conventional single or double cladding structure.

The TCF has another feature. Figure 2 shows a simulated wavelength dependence of an overlap factor Γ of the LP_{02} mode

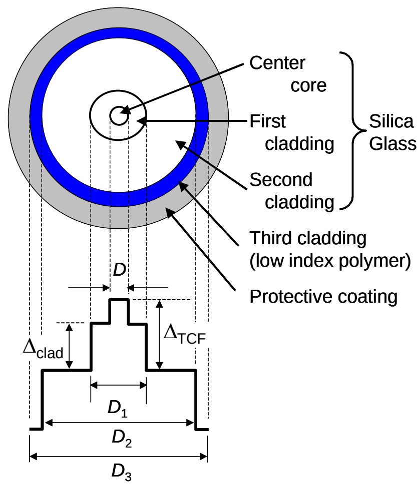

Fig. 1. A schematic refractive index profile of a triple-clad large-mode-area fiber.

in the TCF shown in Fig. 1. Here, Γ is an overlap factor between the guided modes and the core region (Yb-doped region) defined as:

$$\Gamma = \int_{core} |\phi(x,y)|^2 dxdy \Big/ \int |\phi(x,y)|^2 dxdy \,. \qquad (1)$$

In Fig.2, the core diameter D of 30 μm, the first cladding diameter D_1 of 90 μm, the second and third cladding diameters, D_2 and D_3, of 400 μm and 450 μm are used in the simulation. Refractive index of core Δ_{TCF} and refractive index of the first clad Δ_{clad} are 0.40 % and 0.30 %, respectively. The simulated bending diameter is 136 mm. The second cladding is assumed to be pure silica with refractive index of 1.44963 at 1064 nm and the third cladding is a low index polymer material with refractive index of 1.376. The Γ parameter decreases to 0.4 around 1060 nm wavelength region. The Γ value of 0.4 means that the power of LP_{02} mode in the core of the bent fiber is 4 dB decreased compared to that of the straight fiber in whole longitudinal part of the bent fiber. The LP_{02} mode suppression effect can be observed in not only a triple cladding structure but also a double-cladding structure without polymer clad. The LP_{02} mode suppression in a bent fiber is very useful for enlarging a core diameter because many fibers used in a fiber laser are bent in storage.

We have fabricated a double-cladding fiber without polymer cladding in order to verify the simulated Γ reduction. Figure 3 shows a measured refractive index of a fabricated fiber. The fiber is fabricated with MCVD and does not have a third (polymer) cladding in Fig. 1 for ease of measurement. D, D_1, D_2, Δ_{TCF} and Δ_{clad} of the fabricated fiber were 30 μm, 90 μm, 394 μm, 0.5 % and 0.4 %, respectively. The index profile of the fabricated fiber was similar to the step profile used for the simulation.

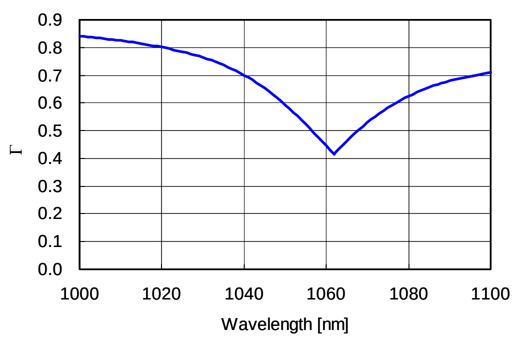

Fig. 2. The wavelength dependence of the Γ parameter of LP_{02} mode at a bending diameter of 136 mm.

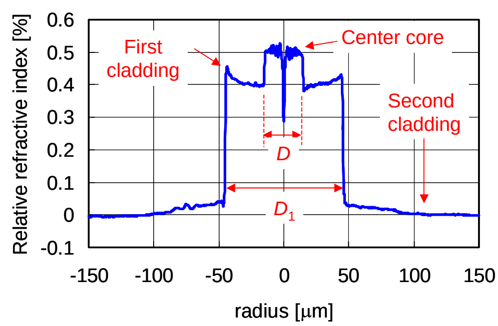

Fig. 3. The refractive index profile of a fabricated fiber.

3. Measurement Setup

Figure 4 shows a measurement setup of a mode-coupling loss. Light source was a super luminescent diode (SLD) light source or white light source. The light source is connected to a fiber under test (FUT) via a launching fiber that was designed to excite LP_{02} modes of the FUT efficiently. Output power from the FUT was introduced to an optical spectrum analyzer (OSA) via a detection fiber, which was a 30-μm-core single-cladding fiber and was used to eliminate cladding modes in the FUT.

A mode coupling loss P is given by P_1-P_0 [dB], where P_0 [dB] is a monitored power without an additional loop and P_1 [dB] is a monitored power with the additional loop. If LP_{01} and LP_{02} modes are fully excited in the FUT and the FUT are bent with a diameter of 136 mm, 60 % power of LP_{02} mode will be coupled to cladding mode and the coupling loss P of −1.55 dB can be expected at 1064 nm wavelength according to the simulation result.

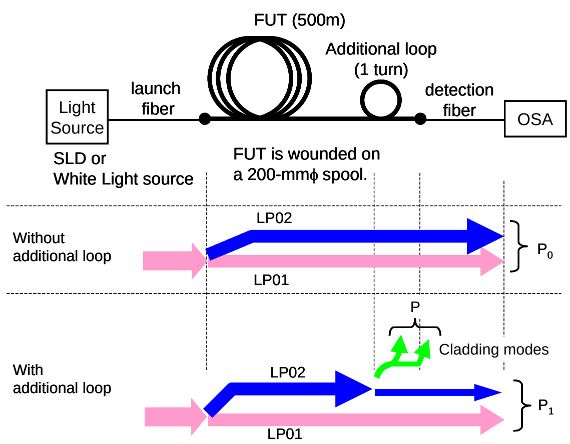

Fig. 4. Measurement set up for a mode-coupling loss.

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4. Measurement Result

Figure 5 shows a wavelength dependence of a mode-coupling loss of a fabricated fiber. An SLD light source was used to realize an enough dynamic range to find a loss peak caused by the mode coupling. The diameter and number of turns of an additional loop were 130 mm and 1 turn, respectively. A loss peak around 900 nm of about 1.2 dB shows that the power of LP_{02} mode is reduced by about 3 dB under the assumption that both the LP_{01} and LP_{02} modes are equally exited: $\Gamma = 0.5$. The wavelength of the loss peak around 900 nm is 150 nm shorter than the predicted wavelength by simulation. The wavelength shift may be caused by the difference in the index profiles between the simulation model and the fabricated fiber.

Figure 6 shows wavelength dependence of coupling loss for various loop diameters. We used white light source to monitor wavelength shift of loss peak over wide range from 600 nm to 1400 nm. The loop diameter was ranged from 100 mm to 160 mm. No loss peak is observed for the loop diameter of 160 mm. However, clear peaks are observed for loop diameters less than 160 mm. The wavelength of the loss peaks shifts to shorter wavelength with decreasing the loop diameter. A loss peak around 950 nm for loop diameter of 110 mm (pink line) is a coupling loss to a second order cladding mode. Figure 7 summarizes bending diameter dependence of peak wavelength. Red and blue solid symbols are measurement data of peak wavelength of mode coupling from LP_{02} to first order cladding mode and from LP_{02} to second order cladding mode, respectively. Solid lines are linear approximations of measured data. The peak wavelength shifts proportionally with the loop diameter.

From the viewpoint of the natures of bent TCF of the simple index profile and the controllability of coupling wavelength by bending diameter, the TCF would be highly useful for a fiber laser application.

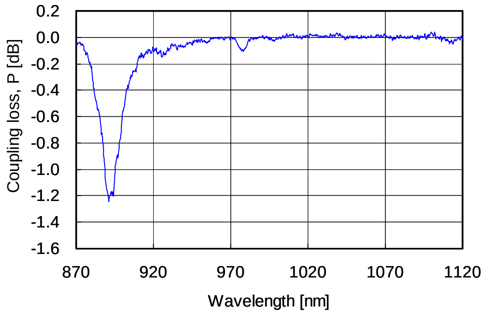

Fig. 5. Measured wavelength dependence of coupling loss *P* for an additional-loop of 130 mmϕ, 1turn.

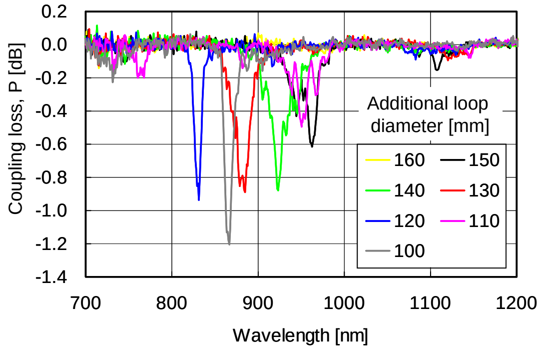

Fig. 6. Measured wavelength dependence of coupling loss *P* for a various additional loop diameter.

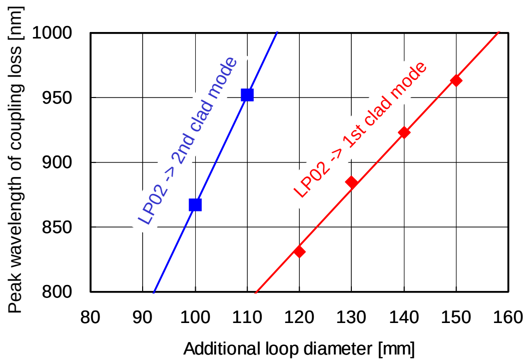

Fig. 7. Peak wavelength of coupling loss as a function of bending diameter.

5. Conclusion

We have experimentally verified the LP_{02} mode suppression thanks to a mode coupling effect in a bent double-cladding fiber. A 3-dB suppression of LP_{02} mode was observed in a fabricated fiber with an additional loop of 130 mm diameter. The peak wavelength shift of the mode coupling loss showed a clear proportional relationship to the bending diameter. The simple higher-order mode suppression technique employing a bent multi-cladding fiber will be useful for a fiber laser application.

6. References

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